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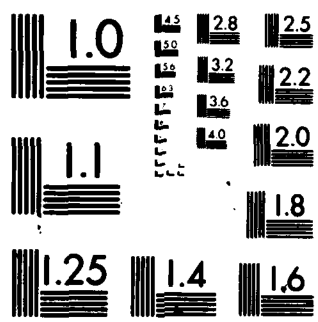
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LEVEL II

AIR FORCE
LOGISTICS COMMAND
OFFICE OF INTELLIGENCE

AD A093351

# A METHODOLOGY FOR ASSESSING AND MINIMIZING THE LIFE CYCLE COST OF A WEAPON SYSTEM USING INTELLIGENCE ASSESSMENTS OF FUTURE MATERIAL AVAILABILITY

1 OCTOBER 1980

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This methodology determines a new way of projecting material price or availability that accounts for the potentially substantial effects of war, revolution or political realignment in material producing nations. This technique is then applied to the optimization of weapon system cost in the design stage. The cost effectiveness of several strategies (e.g., stockpiling, recycling) for avoiding or minimizing the effects of material shortage is discussed using this method of pricing. The impact of material availability on force readiness is considered throughout the text.

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# A METHODOLOGY FOR ASSESSING AND MINIMIZING THE LIFE CYCLE COST OF A WEAPON SYSTEM USING INTELLIGENCE ASSESSMENTS OF FUTURE MATERIAL AVAILABILITY

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## TABLE OF CONTENTS

## ABSTRACT

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## PREFACE

This methodology study was undertaken because of the growing concern by the Air Force for the reliability of foreign sources of materials that are critical to the present and future readiness of our weapon systems. After several discussions with individuals responsible for addressing this issue, it became apparent that there were many potential solutions to specific problems; however, the uncertainty of world events and their impact on resource availability made selection of any alternative very difficult. The variables that needed enlightenment in this problem of acquisition and logistics—the uncertainty of world events and their impact on material availability—were in fact problems for intelligence and hence our involvement. It was also apparent, however, that any intelligence assessment addressing the problem must provide as near a quantitative solution as possible since the merits of alternative courses of action were largely based on economic criteria. Lacking a readily available model for this purpose the development of a methodology was indicated and this effort is the result.

Due to the several academic areas on which this analysis is founded, it was regretfully necessary to simplify many concepts in these diverse disciplines in order to keep the logic of the analysis foremost in the reader's mind. It is hoped that those with special expertise in any of these disciplines will graciously accept the slighting of detail in their area of competence so that readers in other professional disciplines do not become hopelessly enmeshed in academic areas beyond their experience. These omissions must of course be considered in any application of the methodology and much thought and discussion has been given to the impact these would have on the feasibility of this approach. Any substantive errors resulting from such omissions are entirely the fault of the author and not attributable to those who were kind enough to review this work.

The author gratefully acknowledges the contributions and criticisms of the following individuals in preparing this study—Dr. David Miller, Wright State University, for his review and refinement of the mathematics and his consideration of the general validity of the methodology; Captain Larry McNeese, Air Force Institute of Technology, for his review of the economics and mathematics; Dr. Robert Allen, Air Force Institute of Technology, for his review of the economics; Captain Terry Luetinger, Aeronautical Systems Division, for his assistance in preparing the life cycle costing portion of the study; Wayne Norbey and Thomas Murray of the Central Intelligence Agency's Information Science Center and Lieutenant Colonel Dennis Hodsdon of the Defense Intelligence Agency's Defense Intelligence School for their review of the early drafts of the paper and several suggestions that were incorporated into the final copy. In general, the Information Science Center and Defense Intelligence School deserve acknowledgement for their curricula in quantitative analytic techniques relating to intelligence analysis. Finally, Dr. William Stoakley, Defense Intelligence Agency's Research Directorate—Africa, for his collaboration on a preliminary study and his considered thoughts on the use of subjective probabilities in intelligence analysis.



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# INTRODUCTION

The evolution of weapon systems is characterized by the demand for increasing size, numbers, and use of sophisticated technologies. These have required increasingly greater use of special materials, many of which are procured entirely from foreign sources. This import dependence is a potential threat to the readiness of military forces as the curtailment of resource production or export could mean inadequate material supplies from which to manufacture new systems or spare parts. The use of these materials however substantially enhances weapon systems' performances, conferring capabilities that might be achieved by other means only at great expense. Foregoing use of these materials therefore could have equally serious consequences for military capability if weapon systems are unaffordable. The problem imposed by this dilemma on those who acquire and support these systems can be defined as: "Considering the future availability of materials, (1) what materials content will minimize the life cycle cost of a weapon system and (2) what impact will this have on the readiness of the weapon system?" This methodology (1) optimizes system cost with respect to projected material availability and (2) gives a total system cost that includes a cost measurement of the effect of material availability on readiness.

In order to accomplish the latter objective, readiness must be defined and measured in terms of cost. In fact the greater part of readiness is a matter of the amount of money spent on it since in general the engineering of system reliability and maintainability, the quality of support and even the quality of management can be adjusted to the degree desired within the constraints of physical possibility by the application of money to the problem. A system's readiness is impaired when it becomes unaffordable. Hence even a system optimized with respect to projected material availability may not meet readiness criteria if those who control the purse strings are unable or unwilling to spend the money on it. The actual determination of the affordability and therefore degree of readiness of the system is of course a political decision and hence an exogenous factor in this analysis.

# SECTION I

# EXPECTED MATERIAL PRICE

In order to minimize life cycle cost as well as measure readiness with respect to the affordability of materials, it is necessary to know the price that will be paid for them at any point in time. This is impossible, but a probabilistic approach allows an approximate solution. This probabilistic analysis defines the expected material price for a material at any point in time when supplied by any number of suppliers.

Any change in resource availability represents a shift in the supply curve for that commodity with a consequent change in world market price (see Figure 1).[1] The most profound changes would result from a change in government that is accompanied by the destruction of production capability, the flight of technical or managerial personnel, or a change in policy that curtails production or embargoes exports of the resource; these changes could come about by war, revolution, or legitimate electoral processes.

Changes in the producer nation's capability to continue production and its willingness to supply weapon system manufacturers are the most likely effects on availability. These changes or availability effects are reflected by the shifts in the resource's supply curve depicted in Figure 2[2,3]. An intelligence estimate that is a probability assessment of the likelihood of each case being realized can be applied to the consequent material price in each of these cases, i.e. $p_0$ through $p_3$, and the expected material price p' for a discrete political disposition can be calculated using the probability diagram of Figure 3. This expected material price is the sum of the material prices under each case multiplied by the probability of the case occurring. The range of discrete political dispositions that a producer nation's government might assume is incorporated into this calculation and the resultant probability diagram is shown in Figure 4 where these discrete dispositions are simply designated left, center and right.

The cogency of evaluating material price by this method is illustrated by considering the procurement of a material supplied by a single producer or controlled by a commodity cartel. Here there is virtually complete control over the description of the supply curve by the producing element and changes in productive capability or export policy can affect extreme shifts in that curve (see Figure 5). Even a low probability of the worst case occurring may effect a substantial increase in the expected material price, hence using this analysis to acquire a weapon system will constrain the use of materials under monopoly control unless their continued supply is reasonably assured.

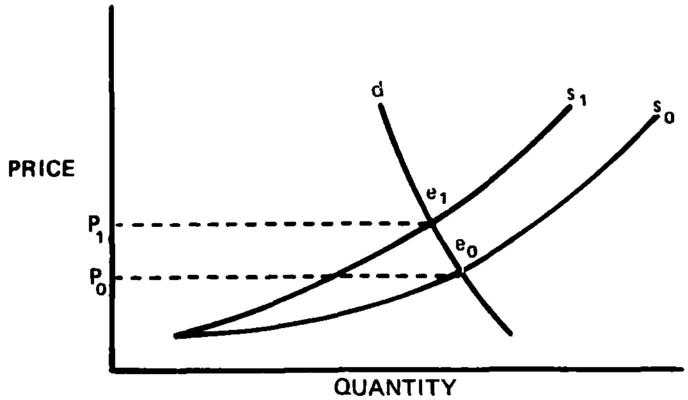
Varying the material content of a weapon system directly varies the total material resources needed for the fleet which may be considerable. As planners consider acquiring a system over the range of material contents of which it may be comprised, the world demand and hence price of the material may vary as well. This has been noted for titanium where an order for a single Boeing 747 will increase the world price of that metal[4]. Expected material price can account for price increases due to demand.

[1]Throughout the methodology, there is no attempt to accurately depict the graphical representation of shifts in supply curves which in reality assume different orientation to the original curve depending on the reason for the change in supply.

[2]These supply curves represent the world market supply from the U.S. perspective. This differentiation is necessary because a producer nation's unwillingness to supply U.S. consumers does not prevent the commodity from reaching them through intermediaries.

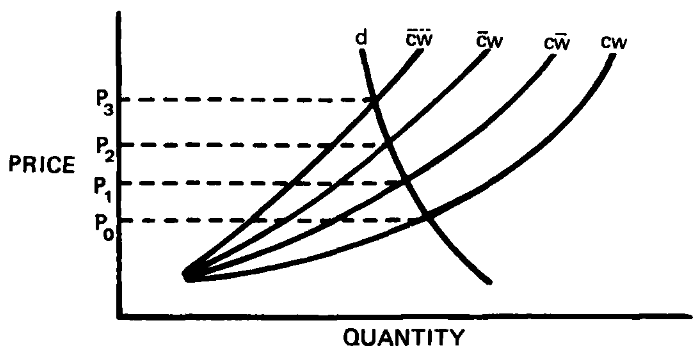
[3]The case where the producer nations may cut back production is another availability effect that may be appended to the analysis. In certain cases, this action could have a greater impact on supply to U.S. consumers than absolute unwillingness to trade with the U.S. since even in the absence of enforcement of the embargo, there may be no material available for U.S. consumers regardless of willing intermediaries.

[4]Leutinger, T. L., unpublished study by Air Force Systems Command, Aeronautical Systems Division, 1979.



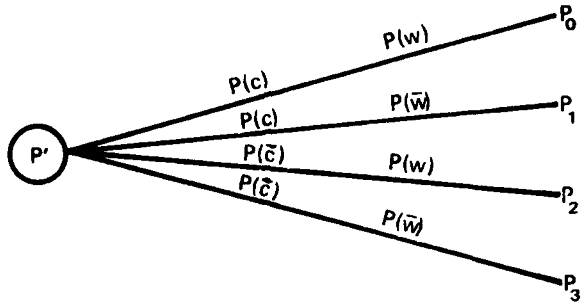

A change in a commodity's availability corresponds to a shift in its supply curve from $s_0$ to $s_1$ resulting in a new equilibrium $e_1$ at the intersection of the new supply curve and the demand curve d. This determines a new market price $p_1$.

**Figure 1**



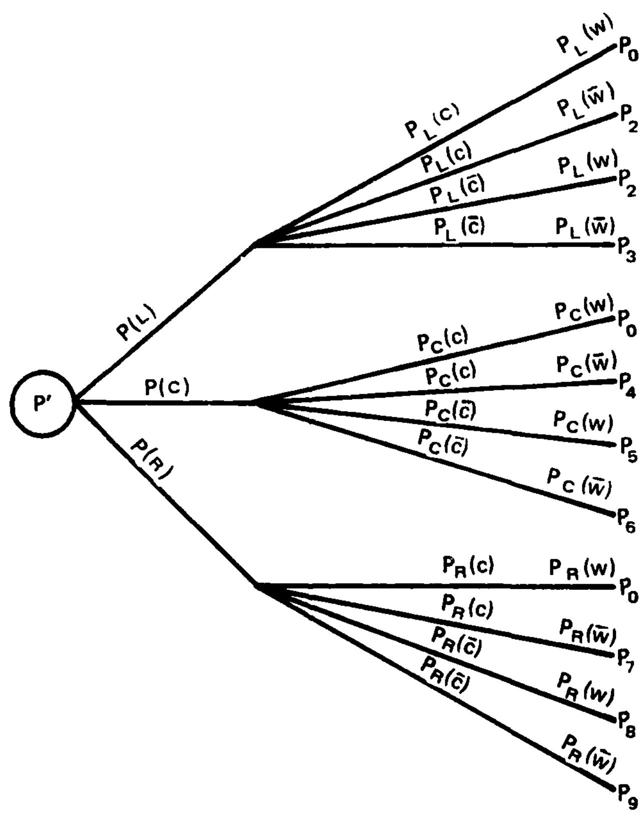

The four potential effects on supply from a change in government come from a consideration of whether or not the change leaves the government capable (c) or not capable ($\bar{c}$) of producing the resource and whether the government is willing (w) or not willing ($\bar{w}$) to supply it. Since each possibility represents a change in resource availability these determine four prospective supply curves with corresponding material prices $p_0$ through $p_3$.

**Figure 2**



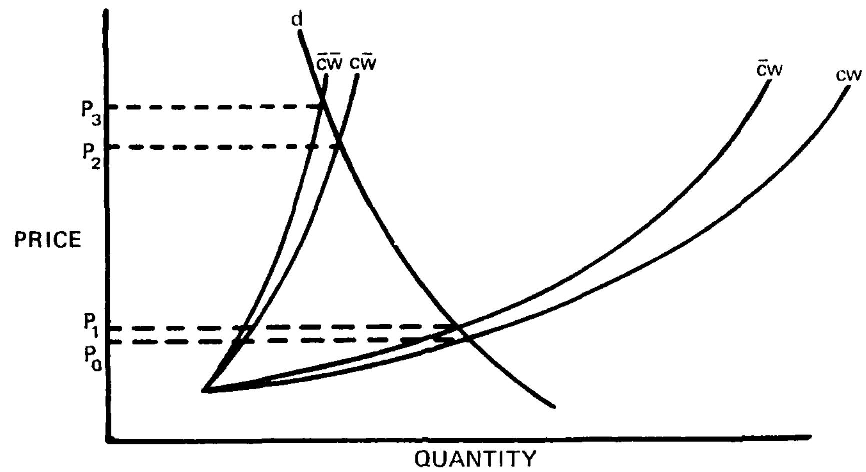

An expected material price p' is calculated from the prospective material prices in Figure 2 and the probabilisticly formulated intelligence assessments of any case being realized. P(c) and P(w) are respectively the probabilities that a particular government will be capable and willing to supply the resource.

**Figure 3**




Expected materia! price defined to include the range of possible political dispositions a government might maintain. In all cases in which a government is capable and willing this is deemed to mean there is no change in price from the original equilibrium price $p_0$.

**Figure 4**




The potential effect on price of monopoly control of a commodity. Here the change in government will have a substantial effect on price if the new government is unwilling to trade.

**Figure 5**

As world demand increases by $\Delta M$ due to the material demand m for an individual weapon system, the demand curve shifts rightward to d' and a new equilibrium price is established at $M_e + \Delta M$ (see Figure 6). Material price is now a function of demand or

$$p(m) = D(M) \tag{1}$$

Expected material price is calculated substituting p(m) for p in Figure 4 where material price is sensitive to material demand. Figure 7 is the demand sensitive graph of Figure 2.

To refine the accuracy and introduce flexibility into the calculation of expected price, the probability of a government having a particular political disposition or occupying any point on the political spectrum can be represented by a continuous function of the relative frequency of that disposition occurring (see Figure 8). The area under the curve between any two points on the political spectrum in Figure 8 represents the probability of that portion of the political spectrum being realized. Description of the posture or disposition of a government in this manner permits refinement of the analysis to any desired degree by partitioning the spectrum into as many discrete segments as needed. Partitioning the spectrum into three equal divisions from left to right yields the discrete set of probabilities used in Figure 4 to develop the methodology. The probability of any partition is

$$P(\gamma_i) = \int_{\gamma_{i-1}}^{\gamma_i} f_\gamma(\gamma_i)\, d\gamma \tag{2}$$

where $P(\gamma_i)$ is the probability distribution and $f_\gamma\ (\gamma_i)$ is the frequency density function for a particular government. In a similar manner, density functions for the consequent capability and willingness of a particular government are defined in Figure 9. The probabilities of a particular disposition being capable or willing are respectively

$$P(C|\gamma_i) = \int_{\gamma_{i-1}}^{\gamma_i} f_C(\gamma_i)\, d\gamma \tag{3}$$

and

$$P(W|\gamma_i) = \int_{\gamma_{i-1}}^{\gamma_i} f_W(\gamma_i)\, d\gamma \tag{4}$$

With the proliferation of possible outcomes for supply when considering a number of political dispositions, it becomes necessary to specify functions $\epsilon(\gamma_i)$ that formulate the economic results of any outcome. That is given a particular political disposition the function will specify the resultant material prices for any set of availability effects.

Using these expressions in the calculation of expected price it is both convenient for notation and execution to express these quantities as matrices. Where

$$C_i = \left[P(C|\gamma_i)\ P(C|\gamma_i)\ P(\bar{C}|\gamma_i)\ P(\bar{C}|\gamma_i)\right] \tag{5}$$

$$W_i = \begin{bmatrix} P(W|\gamma_i) & 0 & 0 & 0 \\ 0 & P(\bar{W}|\gamma_i) & 0 & 0 \\ 0 & 0 & P(W|\gamma_i) & 0 \\ 0 & 0 & 0 & P(\bar{W}|\gamma_i) \end{bmatrix} \tag{6}$$

*and*

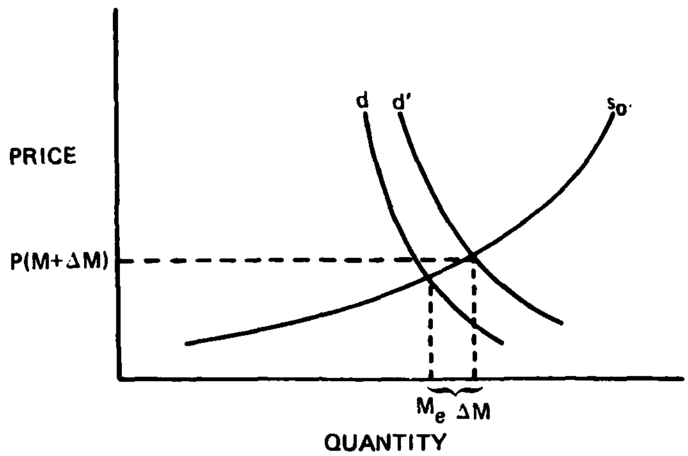
$$\epsilon_i = \begin{bmatrix} \epsilon_{CW}(\gamma_i) \\ \epsilon_{C\bar{W}}(\gamma_i) \\ \epsilon_{\bar{C}W}(\gamma_i) \\ \epsilon_{\bar{C}\bar{W}}(\gamma_i) \end{bmatrix} \tag{7}$$

expected material price for any number of discrete political dispositions n can be defined by

$$p' = \sum_{i=1}^{n} P(\gamma_i) C_i W_i \epsilon_i \tag{8}$$

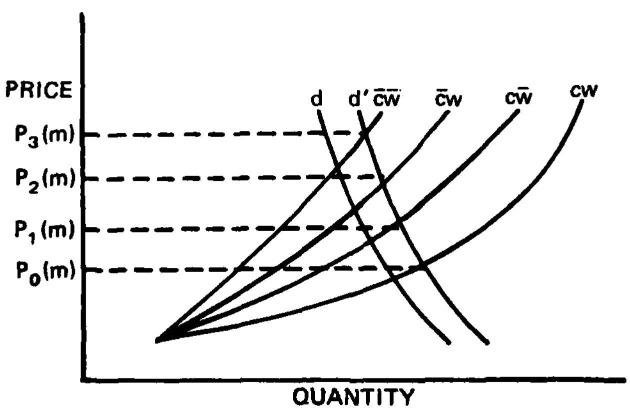
Most strategic resources will have several suppliers resulting in a number of possible outcomes for the availability of a material when the permutations of political positions, production capabilities, and export policy are considered. For example, countries A and B may both face changes in government that result in their occupying left, center or right positions on the political spectrum resulting in nine possible combinations of outcomes for both (see Figure 10A). For each combination of outcomes for these, there are four potential effects on productive capability; where both are capable, one is and the other isn't, and neither are capable of maintaining production. Similarly for each case affecting capability, there are four cases for willingness to supply the commodity resulting in a total of 144 potential outcomes for the supply of a commodity when it is produced by two countries and three potential political dispositions are considered for both (see Figure 10B).

Over time the political disposition of a government is likely to change, reactionary governments may face revolutions, or revolutionary governments may become more moderate. These changes represent shifts in the probability of a government having a particular political disposition; i.e., shifts of $f(\gamma)$ over time as shown in Figure 11. Similarly productive capability and willingness to trade may exhibit dynamic behavior. As shown in Figure 12; for example, productive capability may become more independent of political disposition over time while willingness to trade may remain the prerogative of one political faction. In all three cases, these families of curves are projections from continuous curves for Equations 2, 3, and 4 over time. Generalizing these equations to include time permits the calculation of expected material price at any point in time $p'(t)$ which is the essential requirement to accomplishing the objectives of the methodology.



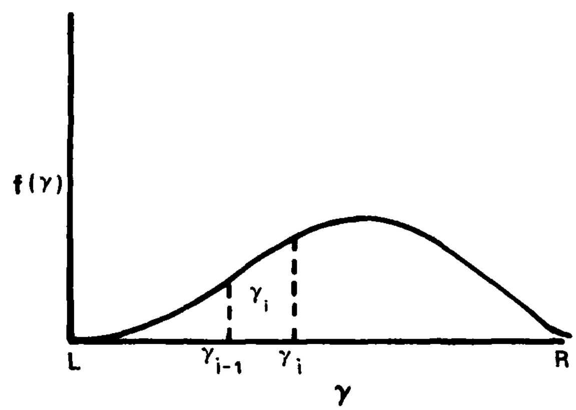

The effect of a change in demand on price. The price of material is determined by the incremental demand increase for material $\Delta M$ over the equilibrium world demand $M_e$.

**Figure 6**



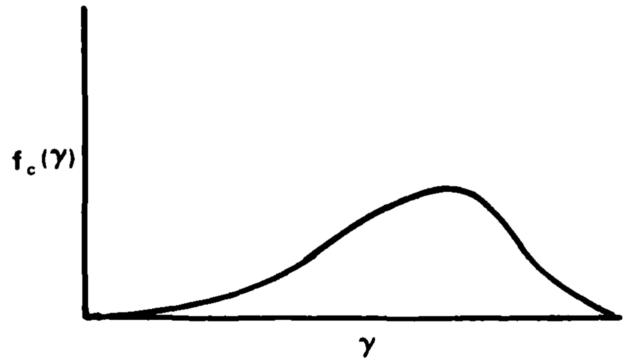

Demand sensitive material prices for the expected price analysis.

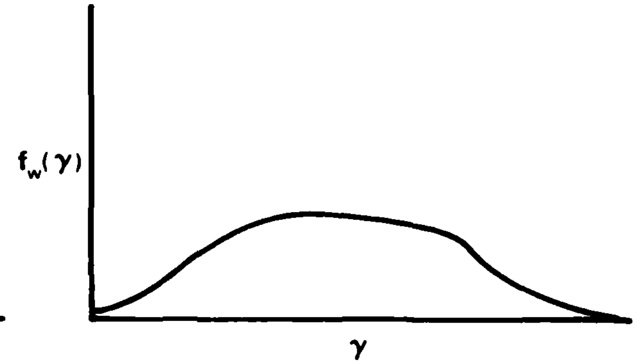
**Figure 7**




A continuous function $f(\gamma)$ for the relative frequency f of a particular political disposition $\gamma$ occurring. The area under the curve between any two points is the probability of that disposition occurring.

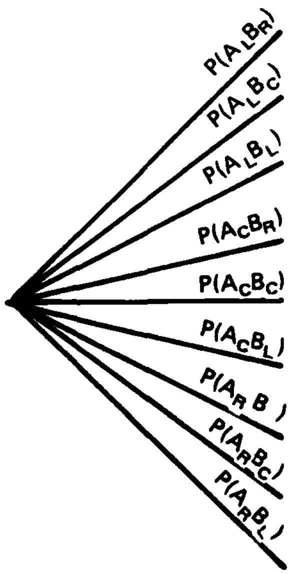
**Figure 8**

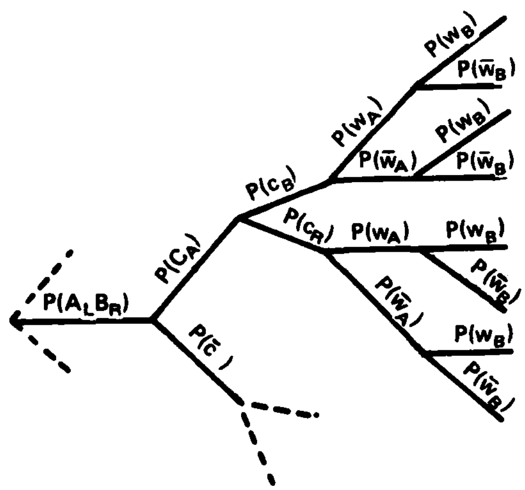



Continuous functions $f_c(\gamma)$ and $f_w(\gamma)$ for the relative frequencies of capability and willingness to trade as a function of political disposition.

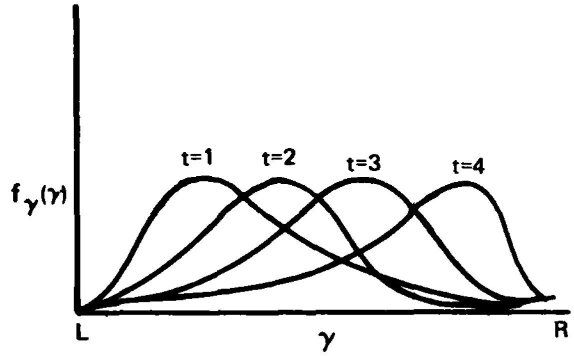
**Figure 9A** **Figure 9B**



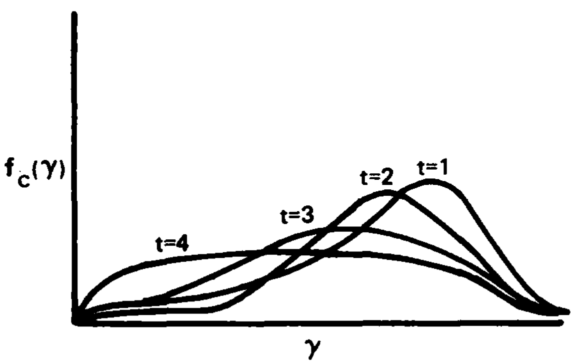

*The probability function for the possible combinations of political dispositions of two countries supplying the same commodity when three potential dispositions, left, center and right, are considered for each.*

**Figure 10A** **Figure 10B**



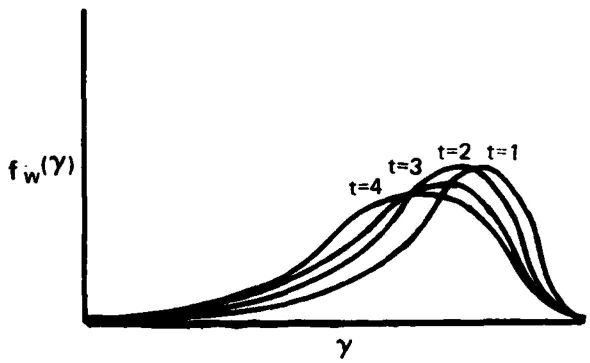

The probable political disposition of a government changing from left to right over time.

**Figure 11**




The probability of a resource producing nation's production capability becoming independent of political disposition over time.

**Figure 12A**




The probability of a resource producing nation's willingness to trade remaining essential of a prerogative of right of center governments.

**Figure 12B**

## SECTION II

## LIFE CYCLE COST OPTIMIZATION USING EXPECTED MATERIAL PRICE

The optimal material content for a weapon system is the least costly mixture of materials that will provide the desired performance. Its determination is critically important because in most cases the material content at the time of acquisition locks in the tooling, manufacturing processes and maintenance concepts needed to produce and support a system throughout its life. The initial requirements for material established at the time of acquisition must thereafter be met regardless of cost if the system is to remain a viable tool for defense.

A definition of the life cycle cost of a weapon system that illustrates the application of expected material price to this optimization problem is: the cost of hardware, spare parts, operation, maintenance, and the costs of development (research, testing, etc). Material content directly varies costs such as those for hardware and spare parts and indirectly varies costs such as maintenance where varying the material content may vary the durability of components necessitating more or less frequent servicing. Since all of these costs are affected in one way or another by material content, the life cycle cost of any component subsystem of a weapon system can be expressed as a function of material content;

$$C(m) = h(m) + s(m) + o(m) + w(m) + d(m) \tag{9}$$

where

m is material content

h(m) is hardware cost

s(m) is spare parts cost

w(m) is maintenance cost

o(m) is operating cost

d(m) is development cost.

The life cycle cost of the system is the sum of the component subsystems' life cycle costs or

$$L(m) = C_1(m) + C_2(m) + \ldots + C_n(m) \tag{10}$$

The application of expected material price to the optimization of costs that vary directly with material content can be observed by considering an abbreviated subsystem cost limited to the cost of hardware and spare parts or

$$C(m) = h(m) + s(m) \tag{11}$$

Both hardware and spare parts costs can be expressed as a function of engineering cost and material cost. For spare parts, this is

$$s(m) = e(m) + r(m) \tag{12}$$

where

e(m) is engineering cost

and

r(m) is material cost;

hardware cost is identically expressed.

The material cost is simply the material price times its quantity or

$$r(m) = p \times m \tag{13}$$

The engineering cost function may be a mathematically specified or empirically derived relationship that relates the cost of the necessary amount of engineering required to achieve a specified performance given material content.

In many cases engineering cost decreases with increasing material content due to the properties of the material that introduce the quality being engineered for into the system. In these cases subsystem cost decreases until engineering cost can no longer be offset by the advantages of material increases and will then increase due to the addition of material cost. The point at which subsystem cost is at a minimum corresponds to the desired material content for the manufacture of the component. This relationship can best be illustrated by example. A jet engine specified to produce 10,000 pounds of thrust could be manufactured with 10% or greater cobalt content. At 10% cobalt, extensive and commensurately expensive thermomechanical processing is necessary to achieve the desired reliability and durability in cobalt containing parts. As cobalt content is increased, less engineering is needed as the inherent properties of the cobalt allow the engine to achieve the specified performance. Subsystem cost C from Equation 11 falls as the increased cost of additional cobalt is disportionately offset by the decrease in engineering cost.[5] As engineering cost approaches an irreducible minimum, the total cost C will begin to rise as increases in material content no longer reduce engineering costs and only add additional expensive metal. The graph of this, Figure 13, clearly indicates the desired material content of the engine point $\mu$ to minimize the subsystem cost.

If a spare component, the jet engine for example, is to be manufactured at some time in the future, the price of the material it incorporates will be subject to the economic impact of the political dispositions of the producer governments and therefore is best estimated using expected material price. If this material for spare parts is acquired at time $t_s$ in the future then the expected material price is $p'(t_s)$. Substituting this expression for p in equation 13 gives

$$r'(m) = p'(t_s) \times m \tag{14}$$

the expected material cost function for spare parts.

The cost of the jet engine in the above example can now be considered taking into account the effect of the change in material availability projected by intelligence assessments. Substituting the expected material cost function into the original spare parts cost function gives

$$s'(m) = e_s(m) + r'_s(m) \tag{15}$$

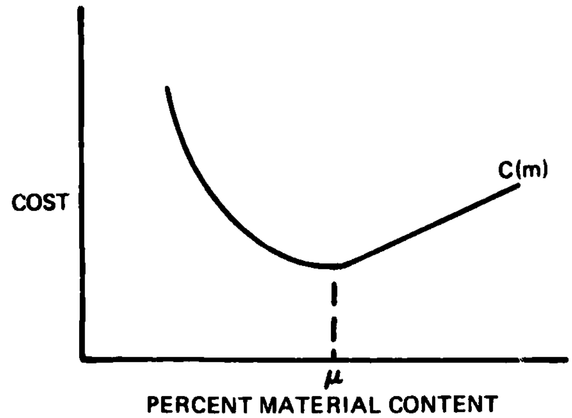
and substituting $s'$ for $s$ in Equation 11 yields

$$C'(m) = h(m) + s'(m) \tag{16}$$

$C'$ is the expected subsystem cost; that is taking into account the probable material price at the time the spare unit will be acquired, this is what the cost curve for this subsystem is expected to look like.

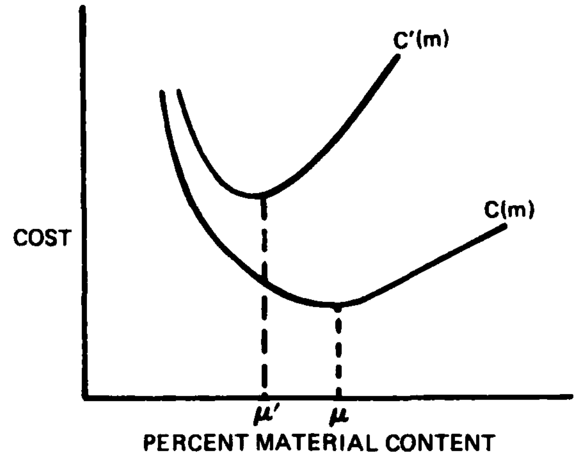
When the risk of material shortage is considered, the minimum of $C'$ is shifted to the left relative to C corresponding to a lower optimal material content (see Figure 14). This is the desired material content to minimize the subsystem cost considering material availability over the life of the subsystem. $C'$ is raised over its domain due to the increased total cost of acquiring the subsystem as a result of a higher average material price over its life. The curve for expected subsystem cost may be thought of as a composite of the cost of a hardware component (e.g., the jet engine) at today's material price when it is to be manufactured plus the cost of a replacement unit at a future material price that is determined by the risk of shortage brought about by political changes in the producer nations.

[5]The cost of a second material that m is obviously replacing here may be considered negligible or absorbed by engineering cost for simplicity in developing this example.




Subsystem cost as a function of material content. In this example the cost of a jet engine decreases as the cobalt content increases until the use of cobalt no longer offsets engineering costs. Material content expressed here in percentage terms can be converted to the specific quantity of material needed for calculations in the text by $m\% \times q = m$ where q is the total material quantity of the component under consideration.

**Figure 13**




Subsystem cost computed conventionally C and computed using the expected cost of spare parts C'.

**Figure 14**

In acquiring a future system, acquisition of the original hardware also will take place at some time in the future when the price of material will be uncertain. Applying the analysis to both the cost of hardware and spares will yield different expected material prices for each which can be used to minimize system cost exactly as was done above. That is,

$$C'(m) = h'(m) + s'(m) \tag{17}$$

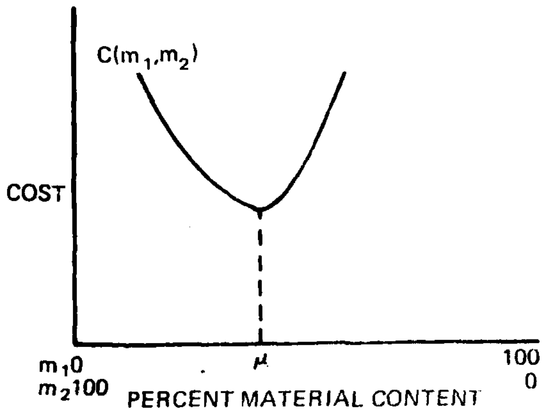
For a subsystem incorporating two or more materials, the materials composition depends on the relationship between the materials and any constraints such as maximum weight or volume. For two materials, the analysis is exactly as above. Where the second material was assumed to contribute a negligible fraction of the subsystem cost in the example of the jet engine, it can now be considered to behave similarly with respect to engineering and material costs. There will generally be a functional relationship between two complimentary materials so that

$$m_2 = f(m_1) \tag{18}$$

This relationship may specify a volume for volume replacement for example. The graph of a subsystem cost curve for this case is given in Figure 15A.

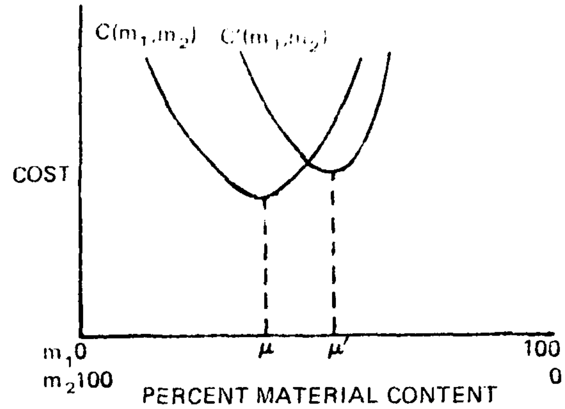
Calculation of the expected subsystem cost in this case is accomplished by calculating expected material prices for both materials and substituting these into the relevant cost functions. The results are graphed in Figure 15B. In general for two materials both subject to potential shortage the optimal material mix will shift toward the one subject to less risk in terms of both the probability of shortage and the cost of material should that shortage occur. When both materials are high risk commodities in this sense, that will be reflected in a high expected subsystem cost. For more than two materials, the same principles apply as long as some functional relationship can be expressed or empirically derived relating material composition to subsystem cost. The general form of these equations can be simplified by expressing material content as a vector,

$$\bar{m} = (m_1, m_2, \ldots, m_n) \tag{19}$$




The graph of the cost of a subsystem containing two materials $m_1$ and $m_2$.

*Figure 15A*




The same graph compared with its expected cost function.

*Figure 15B*

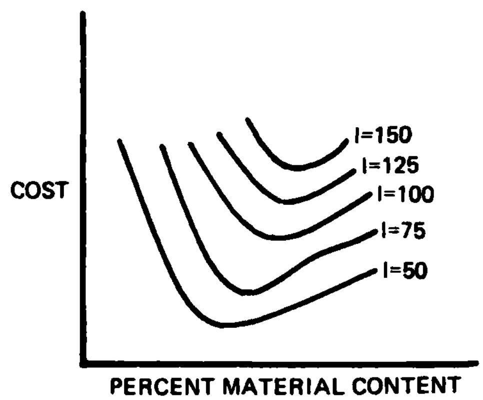
The nonmaterial containing costs for maintenance and development may nonetheless be dependent on material content. Maintenance cost may vary as the decreased use of special materials necessitates more frequent inspection, preventive service, or the accelerated replacement of parts or subsystems. Incurring substantial maintenance costs however may be indicated by the analysis to be the most economical way to obviate the effects of material shortages. Similarly development costs for new processes or substitute materials may be quite affordable when projected life cycle cost considers the economic impact of future material shortages.

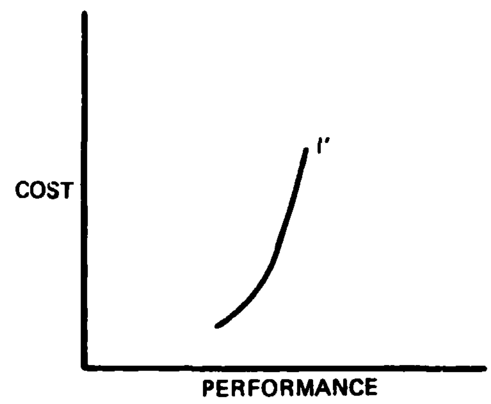
Finally, operating cost is both dependent on the hardware's material composition as maintenance and development costs are, and is an independent consumer of material when fuel is considered as such. Operating cost is a dependent function of material content as the material composition varies the weight or aerodynamic properties of an aircraft for example. It is an independent variable of life cycle cost when fuel efficiency is explicitly engineered for in a system. Here the same trade offs apply to fuel consumption and engineering as applied to nonfuel resources. The cost of engineering fuel economy must be compared to the overall savings in fuel costs considering the expected future price of the fuel. To draw a strict analogy to material containing parts, fuel is a frequently replaceable component whose price may be expected to change with the political disposition of the producing nations[6]. Incorporating the above analyses, the expected subsystem cost function now becomes

$$C'(\bar{m}) = h'(\bar{m}) + s'(\bar{m}) + o'(\bar{m}) + w(\bar{m}) + d(\bar{m}) \tag{20}$$

[6]Petroleum is certainly the present archtype of strategic resources and is a compelling motivation for the application of the methodology. This is due largely to the visibility and epidemic effects of what are actually rather small shortages in percentage terms. These should be placed in perspective against the fact that the U.S. is 50% dependent on foreign sources for our energy needs while 90 to 100% dependent on foreign suppliers for the materials that are the motivation for developing this analysis.

The complete weapon system can be optimized with respect to cost by minimizing its subsystems' costs using the above method. Recalling that the expected subsystem cost curve C′ was generated for a fixed performance, the method can be used to generate a family of curves representing various performance levels for that subsystem. The minima from these curves describe a cost-performance curve (see Figure 16).




Expected cost curves for various performance parameters l (Figure A). The minima from these curves describe a cost/performance curve where performance is a function of material content (Figure B).

**Figure 16A** **Figure 16B**

The required system performance can be achieved by aggregating the various subsystems in combinations that confer this required performance and selecting the least costly option. In this process, subsystem performance in one subsystem is traded off for insured future readiness by reducing the use of high risk materials while the overall system performance is maintained by selecting higher performance subsystems that use low risk materials. For example, where an aircraft's speed is specified as an operational requirement, specific combinations of propulsion and airframe subsystems can be matched to attain the desired performance; less powerful engines could be matched with light airframes, where the risk to engine materials was high and the risk to airframe materials relatively lower. This is expressed

$$\min L'(\bar{m}) = C_1'(\bar{m}) + C_2'(\bar{m}) + \ldots + C_n'(\bar{m}) \quad (21)$$

where $L'$ is expected life cycle cost.

## SECTION III

## STRATEGIES FOR REDUCING EXPECTED SYSTEM COST

With the projection of material price over time several strategies for actively minimizing the effects of nonavailability or high material prices suggest themselves. The benefits of stockpiling are intuitively obvious, however quantification of this option permits an assessment of its capability to insure future readiness. The amount of a material presently stockpiled or capable of being stockpiled with reasonable certainty at a given price can substantially reduce a high expected system cost. The cost of stockpiling must include the direct, indirect and opportunity costs of maintaining it to determine this cost effectiveness. Reversing the analytic process, the stockpile level needed to be a cost effective alternative can be determined. The analysis of expected material price also indicates which material should receive priority or proportionally greater attention in the stockpiling effort. A limited stockpiling or an adjustment of the material acquisition schedule for a system may be a cost effective alternative to high material prices and particularly prices that are demand sensitive. By procuring material in increments over several years prior to its use in manufacturing hardware or spare parts, the multiple price increasing effects of demand and political change could be reduced.

The recycling of scrap is another approach to alleviating the effects of material scarcity. Similar to stockpiling, this option requires an investment that will only yield returns after a number of years when material price and consumption become high enough to recover that investment. To make recycling cost effective, the productive capability must be in place with the appropriate lead time to ensure that necessary quantities of material are available to build spares at a higher material content calculated to save money by reducing system cost. The projected savings in system cost calculated using expected material prices is the motivation for the investment in recycling.

The development of substitute processes and materials offers an alternative to the use of high risk materials. *Frequently however these options only shift reliance from* one strategic resource to another and add additional development costs to the system. While this does not appear to offer a solution, the application of expected price analysis may sharply differentiate between two material consuming processes due to the relative stability of their sources and the severity of price increases that political changes might precipitate indicating the more favorable course of action.

Expected price projection may also be a stimulant to establishing a domestic materials production capability. Materials presently considered unprofitable to mine or refine may not be so in light of projected political influences on this commodity market. Government supports, incentives, or guarantees could be structured to reflect expected price projection to induce domestic production.

This methodology also has application to existing weapon systems. While these systems will be generally constrained to the material composition dictated by design, certain replacement parts might be profitably redesigned to account for material availability. Another perhaps more usable application in this regard is in deciding on repair versus replacement strategies for certain components during the life of a weapon system. The cost of rebuilding certain components may be less than their replacement considering projected material costs. This decision may be made sufficiently in advance of the need for spare parts if the analysis of expected price is continually revised as new intelligence data indicates the more probable political direction a producer nation is taking.

Finally, the questionable availability of a resource may be influenced by implementing strong aid and trade programs, enhancing diplomatic and cultural ties and providing military assistance and training to producer nations. These are all factors that are considered in formulating the probabilistic intelligence estimates that determine expected price (Figures 3 and 4). Here the cost required to favorably change probabilities can be compared to the return realized from lowering the system's expected cost. It may thus be possible to adjust the investment in aid to obtain a net return.

Two measures of the savings to be realized from applying this analysis to the costing of weapon systems are the gross expected savings and the determinant expected savings. Gross expected savings is a measure of the benefit of applying this methodology and a motivation for deviating from conventional price projections. Development of a subsystem at today's material price, that is ignoring risk, will result in an expected cost of $C'(\mu)$ while developing the subsystem at the risk indicated minimum will result in an expected cost of $C'(\mu')$. The gross expected savings is the difference between the two or

$$C_G = C'(\mu) - C'(\mu') \tag{22}$$

Building the system at the risk considered minimum means paying a higher price for the system if all intelligence estimates are incorrect and no material price change occurs. This cost is the difference between the subsystem cost at the nonrisk engineering minimum and the cost of using the material content indicated by considering risk but on the nonrisk cost curve. This is

$$C_I = C(\mu') - C(\mu) \tag{23}$$

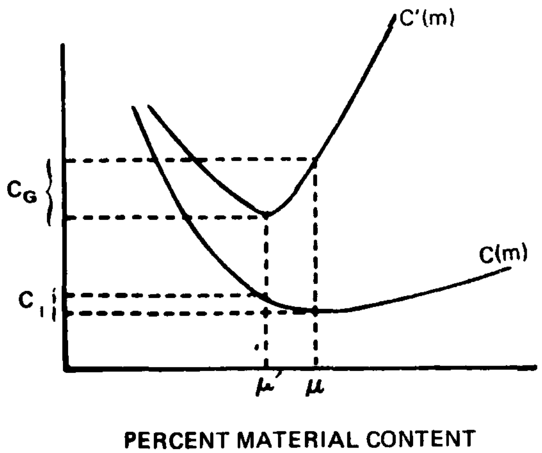
This cost can be thought of as an investment in insurance to minimize the impact of a projected material price increase. The expected return from this investment can be calculated; in percentage terms, it is

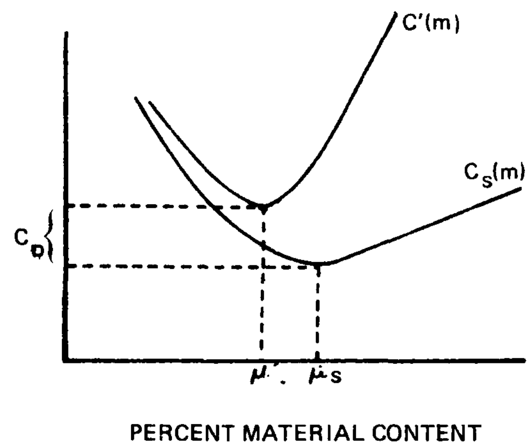
$$R_E = \frac{C_G - C_I}{C_I} (100\%) \tag{24}$$

The determinant expected savings is simply the difference between the minimum expected cost $C'(\mu')$ and the minimum of expected cost determined by the application of the above strategies. That is

$$C_D = C'(\mu') - C_s(\mu_s) \tag{25}$$

A graphical interpretation of these costs is given in Figure 17.




A graphical comparison of the investment cost $C_I$ and the gross expected savings $C_G$ from this investment (Figure A) and a comparison of the expected costs where a strategy to lower expected material price has been implemented (Figure B). The savings from this is the determinant expected savings.

**Figure 17A** **Figure 17B**

# SECTION IV

# CONCLUSIONS

While this analysis does not differ greatly from present methods of arriving at an optimal life cycle cost, its distinction and power is that it considers the potentially substantial impact of political change on world resource economics. On the other hand, this approach is not only subject to the inaccuracies of the conventional econometric analysis on which it builds, but is also constrained by the limits of confidence of the probabilistic analysis it incorporates. Political changes, however, will occur and affect material prices regardless of whether they are anticipated. The attempt to project and quantify the impact of these influences should therefore result in a more nearly optimal acquisition program despite the uncertainty.

The application of this methodology to the development of a material procurement policy that considers future material availability is also intended to avoid overreaction to the present materials posture of the United States. Looking simultaneously at the materials on which weapon technology depends, the source of these materials, and the degree of import dependence, it is almost a reflexive conclusion that the situation is hopeless. This situation is certainly cause for concern but moreover should be cause for the development of an assessment of the future availability of materials and its impact on weapon system development. In the absence of such an analysis conclusions of impending crisis are premature and any economic or political response unwarranted. System acquisition in an environment of unsubstantiated fear for material availability is likely to be as suboptimal as ignoring the problem.

Beyond optimizing individual systems, various alternative solutions to meeting defense requirements may be prompted by viewing readiness through this analysis. The questionable affordability of a proposed system may be obviated by replacing it with a system requiring less high risk materials but that can therefore be acquired in greater numbers. Different approaches to requirements may be motivated by projected material availability. For example, air defense requirements might be met by air interceptors or surface-to-air missiles. Missiles are in general less survivable due to their shorter range and lack of mobility. The cost of engineering in the range and mobility necessary to make the destructive capability of the missile equivalent to the aircraft may however result in a less costly system when the aircraft's material requirements are considered using this analysis.

In perspective, this analysis addresses only one dimension of the problematical area of readiness. In many areas of importance the critical constraint to readiness is not material availability. The lead time for forgings, for example, or more generally forging capacity, is presently a severe restriction on aerospace weapon system production. Even in this example, however, the already extant requirements for future forgings are establishing material requirements that will be satisfied in the future under uncertain conditions. Notably, this example also underwrites the validity of using cost criteria in measuring readiness; it is generally acknowledged that sufficient forging capacity could be acquired in several years time if the considerable capital required to do so was available.

Finally, deriving quantitative results from intelligence estimates through probabilistic techniques deserves comment as this methodology demonstrates the more important attributes of this approach. Two of the most significant factors in the decision-making process are (1) having the right information and (2) correctly interpreting that information. These are potentially significant sources of error when using intelligence information due to the usually incomplete data available and the frequently counterintuitive meaning of that data. This methodology and other similar approaches attempt to reduce the error introduced through these sources by translating intelligence estimates into the specific quantitative criteria needed by decisionmakers to address the problem.

This intrinsically reduces error in several ways. A quantitative result from intelligence analysis requires that intelligence users define what measure of effect is appropriate to the problem so that intelligence producers can present resultant data in terms meaningful to the decisionmaker. Interpreting this data through a probabilistic analysis is merely a reflection that the future is inherently uncertain. The advantages in this is in avoiding the tendency of analysts and decisionmakers alike to focus on the "most likely" course of events. The most likely course of events may still only have a small probability of occurring and other courses that may be realized may have consequences that can't be prudently ignored.

Additionally, formulating analysis in this way forces intelligence producers to clarify imprecisions or alternate interpretations introduced by the language of a purely verbal analysis. Similarly it reduces the unavoidable tendency of decisionmakers, given a large volume of data, to selectively perceive its meaning to conform to a particular solution; at the extremes, the most easily implementable or the most highly conservative. In general then, these aspects of this technique serve to reduce error by enhancing the interface between intelligence producer and user while allowing both to concentrate more fully on their respective tasks.

An important corollary advantage of this technique is in enhancing the intelligence analyst's perception of his contribution to the decisionmaking process—the impact of analysis in determining a course of action is very apparent. The impact of the accuracy ascribed to the analysis is also revealed to the analyst as this may be insufficient to distinguish between competing solutions. This can serve to focus future research, establish requirements for more sensitive collection systems and provide both analyst and decisionmaker with an appreciation of the capabilities and limitations of intelligence data and analysis.

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